Programming magnetic ordering for smart micromachines

by Yuan LIU

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the degree of

Doctor of Philosophy

under the supervision of Prof. Dayong JIN, Dr. Gungun LIN,
Dr. Fan WANG

University of Technology Sydney
Faculty of Science

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Certificate of Original Authorship

I, Yuan LIU declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Mathematical and Physical Sciences, Faculty of Science, at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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Signature: Production Note:
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Format of Thesis

This is a conventional thesis consisting of 6 chapters. Chapter 1 is an introduction chapter with a comprehensive literature review. The background, motivation, advances made in magnetic micromachines, challenges, and bioinspired magnetoreception are discussed in detail.

Chapter 2 discusses representative approaches to fabricate ordered magnetic structures.

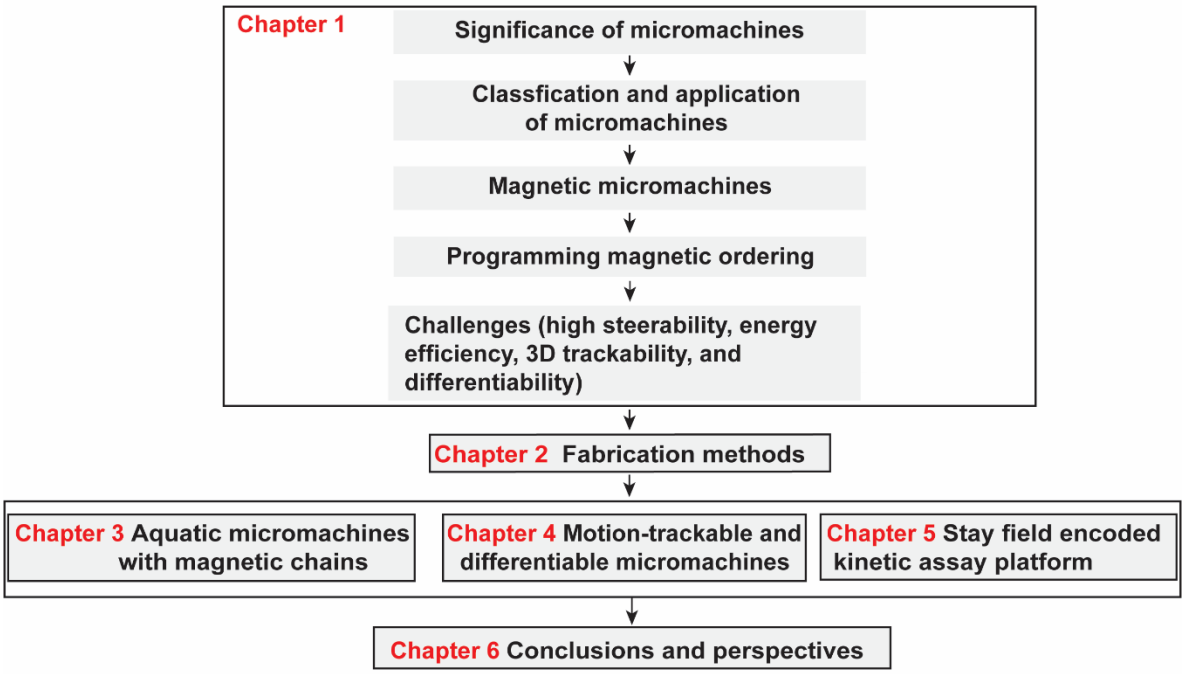
Chapter 3-5 summarise previous investigations of magnetic micromachines with ordered structures.

Chapter 3 examines aquatic micromachines with new functionalities induced by ordering magnetic nanoparticles in polymers.

Chapter 4 introduces 3D motion-trackable and differentiable micromachines based on the compartmentalization assembly of micrometer-scale magnetic building blocks.

Chapter 5 further reports a novel stay-field encoded kinetic assay platform based on the compartmentalization assembly of magnetic building blocks.

Chapter 6 summarizes the main research outcomes of the PhD dissertation and possible future research directions that may arise based on the advances made .


Chapter 1
Significance of micromachines
Classfication and application of micromachines
Magnetic micromachines
Programming magnetic ordering
Challenges (high steerability, energy efficiency, 3D trackability, and differentiability)
Chapter 2 Fabrication methods
Chapter 3 Aquatic micromachines with magnetic chains
Chapter 4 Motion-trackable and differentiable micromachines
Chapter 5 Stay field encoded kinetic assay platform
Chapter 6 Conclusions and perspectives

List of Publications

Articles

1. Yuan Liu[†], Gungun Lin[†*], Yinghui Chen, Ingolf Mönch, Denys Makarov, Bradley J. Walsh, Dayong Jin* "Coding and decoding stray magnetic fields for multiplexing kinetic bioassay platform." *Lab Chip, 2020,20, 4561-4571.* (Cover page of journal: *Lab Chip*, 2020,20, 4506-4506.)
2. Gungun Lin[†], Yuan Liu[†], Guan Huang, Dr. Yinghui Chen, Dr. Denys Makarov, Jun Lin, Prof Zewei Quan, Dayong Jin, "3D Rotation-trackable and Differentiable Micromachines with Bioinspired Magnetoreception for Complex and Dynamic Bioanalysis", *Advanced Intelligent Systems* (2020): 2000205. (Cover page of journal: *Advanced Intelligent Systems* (2021): 202170020)
3. Yuan Liu[†], Gungun Lin[†], Dayong Jin ""Universal Stratified-Disk Architecture for Micro-robotic Functionalization", Submitted.
4. Fang, Guocheng, Hongxu Lu, Hamidreza Aboulkheyr Es, Dejiang Wang, Yuan Liu, Majid Ebrahimi Warkiani, Gungun Lin, and Dayong Jin. "Unidirectional intercellular communication on a microfluidic chip." *Biosensors and Bioelectronics* (2020): 112833.

Patents

Dayong Jin, Gungun Lin, Yuan Liu, "Anisotropic magnetic particles", Australia patent, Lodged. AU2020/903646

Table of Symbol

τ_N	Néel relaxation time
k_B	Boltzmann constant
T	temperature of surrounding environment
K	density of magnetic anisotropy energy
τ_0	attempt time
Re	Reynolds number
ρ_l , ρ	density of the liquid and machine body
μ_l	viscosity of the liquid
$\vec{H}$	external magnetic field
$\vec{B}$	magnetic flux density
$\vec{M}$	magnetization
$\vec{M_r}$	remanent magnetization
H_{ci}	intrinsic coercivity
$\vec{m}_1$,$\vec{m}_2$	magnetic moments of the cores
$\vec{m}_{p1}$, $\vec{m}_{p2}$	permanent moments of the cores
$\vec{m}_{i1}$, $\vec{m}_{i2}$	induced magnetic moments of the cores
$\hat{r}$	unit vector parallel to the line joining the centers of the two magnetic cores/dipoles
μ_0	vacuum permeability
μ_r	relative permeability
r_1, r_2	radius of the micro-scale cores
L	distance between two interacting magnetic cores/dipoles
r_0	radius of the mesoscopic magnetic cores

L_0	spacing between the mesoscopic magnetic cores
χ	magnetic susceptibility
E, E_i, E_p	magnetic energy, energy components of induced moment and permanent moment, respectively
φ_f, φ_i, φ_{ma}	magnetic energy, energy components of induced moment and permanent moment
$\vec{\omega}_{ma}$	rotation frequency of magnetic micromachines
$\overrightarrow{m_n}$	magnetic moment of the n^{th} nanoparticle
N	total number of nanoparticles
ε	shape factor
η	viscosity of the liquid
θ	angle between the magnetic field and uniaxial orientation
l	scale factor of the machine body
F_s	sliding friction force
μ_s	coefficient of kinetic friction
F_n	normal force
C_{rr}	coefficient of rolling friction
U, U_l	interparticle interaction energy
H_e	induced magnetic field from
F_c	centrifugal force
R_{rv}	revolution radius
ω_m, ω_{rv}	angular rotation frequency of the magnetic field and revolution frequency of micromachines
α_{slip}	slipping probability
$F_{surface\ tension}$	lifting force exerted on aquabots from the surface tension for floating
$F_{gravity}$	gravitational force

γ	surface tension coefficient of the water
h_d	height of disk-shaped micromachines
r_d	radius of disk-shaped micromachines
g	gravity
Fi	interfacial force
Fs	shear force
d	diameter of a droplet
Q_1, Q_2, Q_3	Flow rates of inner, middle and outer phase
Q_c, Q_d	flow rate of the continuous phase and disperse phase
l_d	droplet neck width
D	diameter of a collection capillary
v	droplet generation frequency
D_1, D_2, D_3	diameter of inner, middle and outer capillaries
v_1, v_2	droplet generation frequencies of two emulsification steps
N	ratio of droplet generation frequencies (v_1 and v_2)
α, β, φ	rotation angle along the x-, y- and z-axis.
$R_x(\alpha)$, $R_y(\beta)$, $R_z(\varphi)$	rotation matrices that rotate a vector around the x, y, and z-axes
B_s	total effective field that can be detected by a GMR sensor stripe
d_1, d_2 , d_3	inter-peak/valley distance of a voltage signal profile of a microparticle.
S_i	space ratio of inter-peak/valley distance
W_{GMR}, L_{GMR}	width and length of the GMR senor
V_m	magnetic scalar potential

Abbreviations

MNPs	magnetic nanoparticles
SPION	superparamagnetic iron oxide nanoparticles
PAH	poly(allylamine hydrochloride)
PSS	poly-(sodium 4-styrenesulfonate)
PEG-DA	poly(ethylene glycol) diacrylate
DVB	oily divinylbenzene
OA	oleic acid
dMR	disk-shaped micromachines
sMR	stripe-shaped micromachines
DCM	dual-compartment micromachines
MMCs	mesoscopic magnetic cores
MTDM	3D rotation-trackable and differentiable micromachines
NdFeB	neodymium–iron–boron

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Abstract

Smart mechanical systems have greatly extended the reach of human beings in sensing, interacting with, and manipulating objects in the microscopic world. In particular, micromachines can expand our capabilities to access small confined and enclosed spaces, and can be employed for monitoring, diagnosis and treatment of diseases. However, developing micromachines for bioanalysis, which requires the smart integration of power sources, multimodal locomotion, dynamic maneuverability and biosensing functions, remain a formidable challenge.

In nature, living organisms including magnetotatic bacteria have leveraged ordered structures to develop smart and adaptive behaviors. Moreover, advanced materials have been endowed with highly anisotropic mechanical strength and extraordinary functions by creating ordered micro- and nanostructures in the material composition. Along these lines, the present PhD dissertation focuses on systematic investigation of smart micromachines with magnetic structural order, which are fabricated by two major approaches, including magnetic field-assisted self-assembly and photolithography, and microfluidics-directed compartmentalisation assembly of magnetic building blocks.

Based on the above approaches, the first investigation focuses on aquatic micromachines with ordered magnetic nanochains. Multiphase and dynamic maneuverability of micromachines are unlocked, which can bypass the physical constraints of diminishing gravity, dominating surface tension and fluidic drag at the microscale. The 2D planar design of micromachine structures, taking advantage of a Euler's disk-inspired magnetic steering mechanism, enables the ultralight aquatic micromachines with high motility and large-area maneuverability.

The next study investigates a microfluidics-directed assembly of magnetic micro-compartments to build micromachines. The approach is shown to tailor the magnetic coupling between the magnetic building blocks, which endows micromachines with 3D-trackable and differentiable motion. Following this study, a unique set of stray magnetic field fingerprints have been revealed by the inter-compartment magnetic coupling. By hiearachically arranging the magnetic compartments using microfluidic emulsion assembly, a library of encoded magnetic micromachines are generated and shown to be readily decodable by a compact giant magnetoresistance sensor, underlying an streamlined kinetic bioassay platform.

In summary, the series of studies presented in this thesis uncover the physics behind a couple of key functionalities, such as multimodal motility, large-area maneuverability, response tunability, and decodability for smart mobile micromachines. The outcomes of this PhD research project, including fundamental robotic control and proof-of-concept demonstration should inspire future development of micromachines for real-world in-vitro and in-vivo bioanalytical applications.